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(6) SOME STATISTICAL PROBLEMS IN LOGISTICS RESEARCH
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by

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1. Introduction.

Logistics research covers many different areas related to problems of designing and controlling large dynamical systems. In recently published books [3,6] one can find several good discussions of these problem areas and the modern trends in logisitcs research. This research is carried for the purpose of developing efficient management procedures of the total support functions of large systems. We include today among these functions not only the traditional ones, namely: design of facilities; production planning and control, assignment and allocation problems, inventory control, transportation and others, but also problems areas concerned with the reliability and maintainability of weapon systems; tactical mini- and maxi-combat problems, etc. In all the areas mentioned above statistical research occupies a central position. One can find hundreds of papers that have been written on various stochastic and deterministic optimization methods *in each one of the areas* mentioned above. Not much is available, however, in the literature on statistical theories and methods. This is partly due to the complexity of the problems and partly to the widespread practice of applying the established "optimal" procedures in which simple estimates of the unknown parameters are substituted. In many cases such a simple approach yields adequate results. It cannot, however, be always recommended, as will be discussed later.

The objective of the present paper is to expose and discuss some statistical problems, which the author has studied in the past, and to indicate fruitful problem areas for further research. In our exposition we will discuss the following problems:

1) Statistical control of two-echelon multi-station inventory systems;
2) Adaptive manpower forecasting model;
3) Strategies of crossing mine-fields.

These problems areas are not the only interesting ones. There are other interesting statistical problems in the field of logistics research, like problems of evaluating the readiness of systems, reliability estimation, sequential determination of surveillance epochs and others. For some discussion of these problems see Chapter 10 of <u>Modern Trends In Logistics Research</u> [6].

2. Two-Echelon Multi-Station Inventory Problems.

In the present section we give an example of a complicated inventory control problem which requires statistical techniques, since the information on the demand distributions is incomplete. The problem we consider is that of determining optimal stock policies in a two-echelon multi-station model, designed for naval applications. The two echelons under consideration are the depot, D (upper) and tender-ships, $T_1,\dots,T_k$ (lower). The customers arriving at the stations are submarines. We assume that the monthly demand for a specified item, at station T_j is a random variable X_j, $j = 1,\dots,k$.

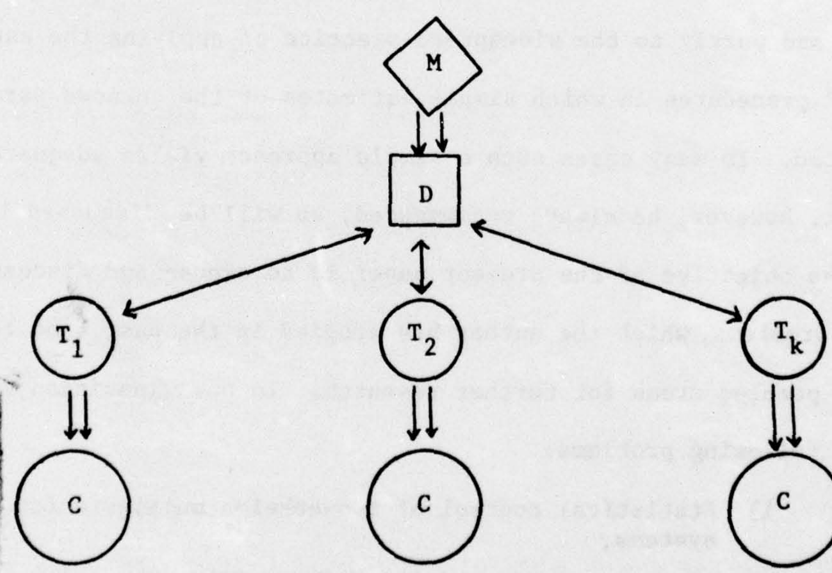

Fig. 1. Inventory flow in a two-echelon multi-station model.

The flow of material in the system is described in Fig. 1. The stations can order from the depot, D, at the beginning of the n-th month a quantity $Y_{j,n}$, or could send back to the depot unneeded stock. If $Q_{n,j}$ denotes the stock level at T_j at the beginning of the n-th month then $Y_{n,j} \geq -Q_{n,j}$, for all $j = 1,\ldots,k$. Moreover, $\sum_{j=1}^{k} Y_{n,j}^{+} \leq V_n$, where $Y^{+} = \max(0,Y)$ and V_n designates the stock level at the depot at the beginning of the n-th month. The depot orders from the manufactures at the beginning of the n-th month a quantity Z_n, which arrives at the depot only ℓ months later. The lead-time between the upper and the lower echelons is one month. The objective is to determine at the beginning of each month order levels $(Z_n, Y_{n,1},\ldots,Y_{n,k})$ so that the expected total lower echelon cost

$$C(\underset{\sim}{Q}_n, \underset{\sim}{X}_n) = \sum_{i=1}^{k} \{c_i(Q_{n,i} - X_{n,i})^{+} + p_i(Q_{n,i} - X_{n,i})^{-}\}$$

will be minimized and the probability that at each month the depot will be able to satisfy the demand of the stations will not be smaller than a pre-assigned tolerance level γ. Zacks and Fennell [11,12] studied the problem when only partial information on the distributions of the demand variables $X_{n,1},\ldots,X_{n,k}$ is available. Bayes adaptive control procedures were developed. These procedures determine after every months, according to the total observed demand at each station, the predictive distribution of the future demand variables. The predictive distributions obtained from the Bayesian model are negative binomial with adaptively changing parameters. The negative binomial distributions were previously fitted by Haber and Sitgreaves [4] to the demand for repair parts in the Polaris fleet. Such distributions were also fitted by Denikoff, Fennell, Haber and Solomon [2]. It was shown in these previous studies that the negative binomial distributions, which depend on two parameters, can provide an adequate fit to the demand distributions of most classes of items in the submarine fleet. In the Bayesian model, if we

assume that demand variables $X_1, X_2, \ldots,$ for a certain part, at different months are, conditionally an θ , independent and identically distributed having a Poisson distribution with monthly average θ , and if θ has a prior gamma distribution, $G(\frac{1}{\tau}, \nu)$, then the expected distribution of X_{n+1}, given that $\sum_{i=1}^{n} X_i = T_n$, is the negative binomial distribution with p.d.f.

$$P[X_{n+1} = i \mid \psi_n , \nu_n] = \frac{\Gamma(\nu_n + i)}{\Gamma(i+1)\Gamma(\nu_n)} \psi_n^i (1 - \psi_n)^{\nu_n} , \quad i = 0,1,\ldots$$

$$\text{with } \psi_n = \frac{\tau}{1 + (n+1)\tau} \quad \text{and} \quad \nu_n = \nu + T_n .$$

This distribution is called the predictive distribution of X_{n+1} given the past history of the demand. The model is thus much more flexible, since the predictive distributions applied for the determination of the optimal stock levels are not the same every month, but keep adapting to the actual results. Algorithms for the determination of the optimal order levels at the lower echelon and the upper echelon were developed. For the proof of optimality of the overall procedure see Zacks [8]. The cost function $C(\underset{\sim}{Q}_n, \underset{\sim}{X}_n)$ looks simple enough, but due to the structure of the inventory flow, the determination of the order vector $\underset{\sim}{Y}_n$ should minimize the expectation

$$R(Y_n ; Q_n) = \sum_{i=1}^{k} E_{i,n} \{ c_i [(Q_{n,i} + Y_{n,i} - X_{n,i})^+ - X_{n+1,i}]^+$$
$$+ p_i [(Q_{n,i} + Y_{n,i} - X_{n,i})^+ - X_{n+1,i}]^- \} .$$

This is the expected cost due to shortage or excessive stock at the end of the (n+1)st month, computed according to the predictive distribution of $X_{n,i}$ and $X_{n+1,i}$, determined at the end of the (n-1)st month. The program for the determination of the optimal $\underset{\sim}{Y}_n$ is not too complicated and the

computations are quite fast. On the other hand, the determination of the optimal upper echelon ordering, Z_n, for a lead-time of $\ell = 2$ months requires to find, at the end of the (n-1)st month the smallest integer z which satisfies the inequality

$$P\{z + Z_{n-1} + V_n \geq \sum_{i=1}^{k} (Y_{n,i} + Y_{n+1,i}) + \sum_{i=1}^{k} (k_{n+2,i} - Q_{n+2,i}) | \underset{\sim}{T}_{n-1}\} \geq \gamma ,$$

where $(k_{n+2,i} - Q_{n+2,i})$ is the desirable ordering level of the i-th station two months in the future. This conditional probability, which depends on the total observed demand, $\underset{\sim}{T}_{n-1}$, at all the k stations during the first $n-1$ months, is a very complicated predictive distribution. In order to approximate it by simpler predictive distributions we have performed extensive simulations of such systems, with the exact computations of the Z_n values. In the following table we illustrate a Six-Station case where the demand variables at each station are independent Poisson with different means, λ.

Table 1. The parameters of a 6-station system.

i	ν_i	τ_i	Q_i	c_i	p_i	x_i	V	Z
1	19.	2.	0	2.	12.	2.	-	-
2	19.	2.	2	4.	10.	4.	-	-
3	19.	2.	4	6.	8.	6.	-	-
4	19.	2.	6	6.	8.	8.	-	-
5	19.	2.	8	4.	10.	10.	-	-
6	19.	2.	10	2.	12.	12.	-	-
Depot	-	-	-	-	-	-	1	0

Table 2. A 12-months simulation of a 6-station system.

n	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	V	Z	COST
1	0	2	4	6	8	10	5	0	0	0	0	0	5	62	108
2	0	0	0	1	0	0	0	0	0	0	0	0	0	1	314
3	0	0	0	0	0	0	10	10	7	10	11	14	62	63	94
4	9	6	2	1	0	0	0	0	0	0	0	7	7	12	312
5	9	0	0	0	0	0	0	10	9	10	15	19	63	66	86
6	6	2	0	1	3	4	0	0	0	0	0	12	12	19	252
7	4	0	0	0	0	4	3	10	10	12	15	16	66	68	120
8	5	7	2	4	7	9	0	1	0	3	6	9	19	19	98
9	3	4	0	0	2	14	5	8	13	15	16	8	68	65	202
10	7	9	11	4	10	11	0	0	0	9	5	8	22	21	252
11	6	4	9	5	7	6	2	7	2	10	11	17	65	49	200
12	5	9	0	8	8	17	2	2	12	7	9	5	37	38	156

This table show that after a few months of correcting a system which is ill conditioned, the system stabilized, and the optimal Z_m values are approximately equal to the sum of the Y_n values only for several months. We have also shown in [11] that the Y_n and Z_n values which are determined by using Poisson distributions with estimates of the λ values, yield average monthly cost larger than the ones obtained by the Bayes adaptive procedure. This illustrates well the need for the development of proper statistical procedures.

3. Adaptive Manpower Forecasting Models.

In the present example we would like to present a forecasting problem which does not belong to the class of problems which are suitable to the commonly used time-series forecasting like those discussed by Box and Jenkins [1]. The problem is that of periodic forecasting of the total size of the Marine Corps, and the size of certain parts of the force. The need for a statistical method of forecasting the size of the force, despite the fact that individuals belonging to the force sign service contracts, is due largely to the problems of random attrition. This attrition is not of constant

proportions at every time period and at different units of the force. Withdrawal from service among the career force personnel is of different characteristics than that of first enlistees. The factors which significantly affect the attrition of the first-term enlistees were studied by Haber [4]. It was found that among many different possible factors the ones which significantly influence the retention rates are: length of contract, year of entry to the force, education and race. These factors are not independent; moreover, the year of entry to the force is an important variable because many of other possible factor of apparent theoretical importance (economical, sociological, psychological and political) are actually time dependent. Thus, if we classify the individuals according to the year and quarter of entry, length of contract, education (less than high school, at least high school) and race (white and non-white) all the other factors do not contribute significantly to the improvement of the forecasting. On the other hand, different parts of the career force show high similarity of retention rates. It was found that one retention rate can be used for the whole career force at each forecasting period. The career force rate shows also small variability over time.

The methodology of forecasting applied in our studies is based on the estimation of the retention probabilities of certain subpopulations over the last quarter, and determining prediction (or tolerance) intervals having the characteristic that, with confidence probability $(1-\alpha)$ we anticipate the size of the groups under consideration to belong at the end of the next quarter to the intervals. Several methods of determining the prediction intervals were compared.

In the following table we illustrate the prediction intervals determined by three methods (conditional maximum likelihood - CMLE; tolerance limits and Bayes prediction limits) as determined on actual Marine Corps data.

Table 3. Prediction limits for the size of cohorts on July 2, 1972 (α = .05). Forecasting on January 1, 1972.

i	j	k	m	CMLE		Tolerance		Bayes		Actual
1	1	1	1	1401.	1434.	1382.	1446.	1393.	1439.	1418.
1	1	2	1	507.	520.	496.	523.	502.	521.	499.
1	2	1	1	3272.	3303.	3253.	3315.	3264.	3307.	3280.
1	2	2	1	676.	693.	665.	697.	671.	694.	674.
2	1	1	1	935.	979.	912.	997.	926.	986.	1009.
2	1	1	2	876.	916.	855.	932.	867.	922.	910.
2	1	1	3	1133.	1165.	1115.	1177.	1125.	1170.	1155.
2	1	2	1	113.	130.	103.	136.	109.	132.	135.
2	1	2	2	98.	111.	89.	114.	94.	112.	104.
2	1	2	3	158.	169.	149.	171.	154.	170.	163.
2	2	1	1	1973.	2009.	1952.	2023.	1964.	2014.	2019.
2	2	1	2	2277.	2309.	2257.	2322.	2269.	2314.	2301.
2	2	1	3	1112.	1133.	1099.	1140.	1106.	1136.	1121.
2	2	2	1	246.	260.	235.	264.	241.	261.	256.
2	2	2	2	223.	236.	214.	239.	219.	237.	230.
2	2	2	3	171.	181.	163.	183.	167.	182.	177.
3	1	1	1	1467.	1518.	1440.	1540.	1456.	1527.	1570.
3	1	1	2	1692.	1749.	1663.	1773.	1630.	1758.	1781.
3	1	1	3	2261.	2325.	2223.	2352.	2247.	2335.	2347.
3	1	1	4	2554.	2616.	2522.	2643.	2541.	2627.	2633.
3	1	1	5	2952.	3001.	2924.	3022.	2940.	3010.	2979.
3	1	2	1	147.	166.	136.	173.	142.	169.	165.
3	1	2	2	167.	187.	156.	194.	162.	190.	190.
3	1	2	3	266.	291.	252.	300.	260.	294.	292.
3	1	2	4	279.	300.	266.	207.	274.	302.	294.
3	1	2	5	391.	404.	380.	403.	386.	405.	386.
3	2	1	1	3333.	3379.	3307.	3399.	3322.	3387.	3403.
3	2	1	2	4623.	4676.	4594.	4699.	4611.	4685.	4675.
3	2	1	3	3380.	3427.	3354.	3447.	3369.	3435.	3416.
3	2	1	4	4115.	4159.	4090.	4177.	4104.	4166.	4108.
3	2	1	5	3207.	3240.	3187.	3252.	3199.	3245.	3207.
3	2	2	1	331.	348.	319.	353.	325.	350.	345.
3	2	2	2	431.	452.	417.	459.	425.	455.	451.
3	2	2	3	411.	432.	397.	440.	405.	435.	428.
3	2	2	4	466.	488.	453.	496.	460.	491.	478.
3	2	2	5	526.	540.	516.	544.	522.	541.	526.
Sums				48170	49249	47537	49656	47902	49404	49130

In the above table, the index i $(i=1,2,3)$ designates the three types of contracts (2,3,4 yrs). The index j $(j=1,2)$ designates the race (W,N-W). The index k $(k=1,2)$ designates the education (LHS,AHS) and the index m designates the time of entering to the force according to the following code:

i	m	Entry
1	1	Jan. 1971
2	1	Jan. 1970
	2	July 1970
	3	Jan. 1971
3	1	Jan. 1969
	2	July 1969
	3	Jan. 1970
	4	July 1970
	5	Jan. 1971

If we denote by $X_{ijkm}(t)$ the size of the (i,j,k,m)-th subpopulation after t periods (of six months) then the basic theoretical model is that, for each such subpopulation the conditional distribution of $X_{ijkm}(t)$ given $X_{ijkm}(t-1)$ is the binomial, $B(X_{ijkm}(t-1), \theta_{ijkm}(t))$; where $\theta_{ijkm}(t)$ is the retention probability for that subpopulation during the t-th period. The CMLE method provides $(1-\alpha)$-prediction intervals for $X_{ijkm}(t)$, given $X_{ijkm}(t-1)$, when the retention probabilities are estimated from the data by the conditional maximum likelihood estimators. The tolerance limits and the Bayes limits are constructed by considering first the $2\text{ARCSIN}(\sqrt{\theta})$ transformation;

$$Y_{ijkm}(t) = 2\sin^{-1}\left(\sqrt{\frac{X_{ijkn}(t) + .5}{X_{ijkm}(t-1) + 1}}\right) .$$

This transformation has desirable characteristics in terms of variance stabilization even for medium size samples. We will not provide here the derivations and the formulae of the prediction limits. The interested reader

is refered to Zacks and Haber [14]. Total force forecasting procedures were applied by the Marine Corps following the technical paper of Zacks [10]. The method was also applied to a problem of forecasting the retention of Navy Pilots.

4. Strategies of Crossing Mine Fields.

The study on strategies of crossing mine fields was performed in 1963-1966 (see Zacks and Goldfarb [11] and Zacks [8]) and renewed recently in a new study, Zacks [15]. The problem can be described in the following terms.

A number of clusters, k, containing $N_1,\ldots,N_k$ mines, are distributed randomly over a (rectangular) field of specified dimensions. The centers of the clusters $(\xi_1,\eta_1),\ldots,(\xi_k,\eta_k)$ are given and the specific bivariate distribution functions, according to which the mines in each cluster are distributed, are given too. The problem is to determine, for any specific breaching path, the survival probabilities of each one of n targets (personnel, vehicles or tanks) crossing in a column at the same path; under the following assumptions:

(i) the encounters of targets and mines are conditionally independent of the prior events;

(ii) with probability p_{det} a mine is detected and destroyed by the target;

(iii) an activated mine destroys the target only with probability p_k ;

(iv) a target passing the neighborhood of a mine activates it with probability p_{act}.

The parameters p_{det}, p_k and p_{act} are specific to the type of target crossing the field and the type of mine used.

The survival probabilities of the targets crossing in a column depend in addition on the number of mines in the path. This is an unknown variable, whose distribution can be often approximated by a Poisson distribution, with parameter, λ , which depends on the location of the path relative to the centers of the k clusters; on the number of mines $N_1, \ldots, N_k$; and on the particular distributions of the clusters. In a recent paper Zacks [15] provided formulae for the determination of the parameter λ when the cluster distributions are bivariate normal, and an algorithm for the recursive (exact) determination of the survival probabilities. In the previous papers of Zacks and Goldfarb [11] and of Parsons [7] closed form formulae were provided for the survival probabilities in the special case of no possible detection $(p_{det} = 0)$ and every activation destroys the target $(p_k = 1)$. Closed analytic formulae can be derived also in the present general model. They are however, of no special interest, because the computation time required is trivial. The procedure developed by Zacks in [15] has been already applied by TRASANA at the White Sands Missile Base for the solution of various problems in the evaluation of new weapon systems.

5. Example.

Consider a squared mine field of dimensions $200m \times 200m$. Nine clusters of $N = 50$ mines are distributed over the field around the center points with coordinates $\xi_i = 50, 100, 150$ m and $\eta_i = 50, 100, 150$ m $(i=1,2,3)$. Each cluster is distributed according to a bivariate normal distribution around its center point with variances $\sigma_x^2 = 81.25\ m^2$, $\sigma_y^2 = 43.75\ m^2$ and correlation $\rho = .5447$. Such a distribution is obtained by a $\theta = 30°$ rotation of a bivariate normal distribution with $\sigma_y = 10m$, $\sigma_y = 5m$ and $\rho = 0$.

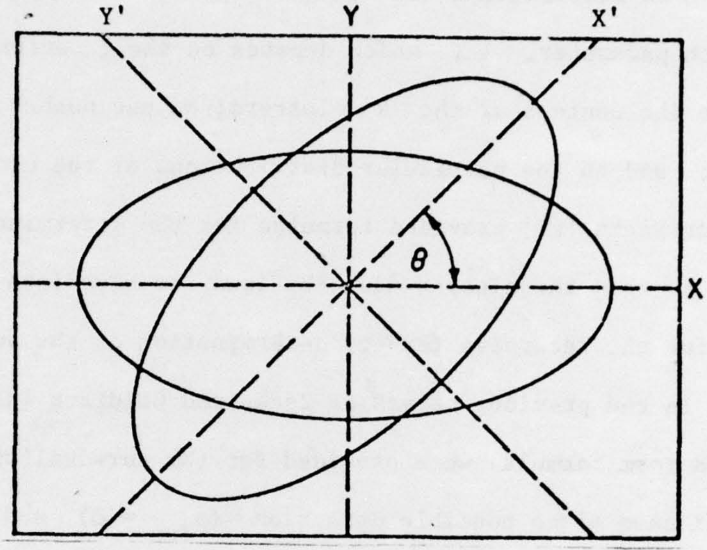

Fig. 2. Ellipsoids of concentration of scatter distributions.

We consider straight breaching paths of width 1m. We compute first the probability ψ_{ij}, that a mine belonging to cluster (i,j) will fall in the breaching path. The distribution of the number of mines in the path is approximated by a Poisson distribution with mean $\lambda^* = 50 \sum_{i=1}^{3} \sum_{j=1}^{3} \psi_{ij}$. Following the algorithm developed in [15] we can determine the expected number of survivors in a column of n. In the following table we provide the values of λ^* and expected survivors in 20 paths located B m from the center of the field.

Table 4. Expected number of survivors in columns of $n=10$, $p_{det}=.4$, $p_{act}=.95$, $p_k=.7$, $p_{dud}=.2$, $n=50$.

B	λ*	$E\{X_n\}$
-95.	0.000	10.000
-85.	0.003	9.999
-75.	0.114	9.953
-65.	1.331	9.452
-55.	4.552	8.127
-45.	4.552	8.127
-35.	1.334	9.451
-25.	0.228	9.906
-15.	1.334	9.451
- 5.	4.552	8.127
5.	4.552	8.127
15.	1.334	9.451
25.	0.228	9.906
35.	1.334	9.451
45.	4.552	8.127
55.	4.552	8.127
65.	1.331	9.452
75.	0.114	9.953
85.	0.003	9.999
95.	0.000	10.000
Average		9.259

There are several interesting statistical problems that can be tackled now. One is the problem of optimal strategies of crossing a field when there is no complete information on the scatter distributions of the mines in each cluster and on the number of mines in each cluster. If this information is available we can easily find the path for which the expected number of surviving targets, out of n crossing in a column, is maximal. One can impose on this maximization problem also additional constraints of the battlefield. On the other hand, when the information needed to compute the distribution of the number of mines in each path is incomplete the decision problem becomes that of choosing from m alternative paths one having the most

favorable distribution of the number of mines in the path. The decision of how to cross the n targets is performed in a sequential manner. According to some prior consideration a corssing path is chosen for the first target. The result of the first crossing attempt (success or failure and the points along the path at which mines were destroyed) leads to a reevaluation of the strategy and a crossing path for the second target is then chosen, and so on. The objective is to find a decision rule for maximizing the expected number of survivors. Zacks [8] studied the problem previously for the case of two crossing paths, in terms of the famous TWO ARMED BANDIT PROBLEM. It is an interesting and quite difficult problem that should be studied. Algorithms of the Dynamic Programming type for the optimal determination of the crossing strategy can be developed.

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The present paper discusses some problems of large systems logistics and tactical decision processes which require the development of the proper statistical theories and methods. The discussion is focused on three problem areas: statistical control of two-echelon multi-station inventory systems; statistical manpower forecasting and survival distributions in crossing minefields. The discussion is general but specific numerical examples are provided to ~~illustrate the ideas.~~

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